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EXECUTIVE SUMMARY

The groundwater flow and radionuclide transport at the Amchitka Island underground nuclear tests are modeled using two-dimensional numerical simulations. A multi-parameter uncertainty analysis is adapted and used to address the effects of the uncertainties associated with the definition of the modeled processes and the values of the parameters governing these processes. The nuclear tests performed at Milrow, Long Shot and Cannikin are the focus of this investigation. These tests were detonated on October 2, 1969, October 29, 1965, and November 6, 1971, respectively. The announced yield of these test are approximately one megaton for Milrow, 80 kilotons for Long Shot and less than five megatons for Cannikin.

The flow model is conceptualized to address the problem of density-driven flow where the saltwater intrusion problem is encountered. The multi-parameter uncertainty analysis addresses the effects of the uncertainty associated with four of the parameters governing these processes on the resulting solution. These parameters are the hydraulic conductivity, recharge, fracture porosity and macrodispersivity. The heat-driven flow and three-dimensional flow features are addressed in a less rigorous manner via a sensitivity analysis. This includes the geothermal heat, the shot-induced heat effects, the chimney geometry, the effects of nearby faults and the effect of the island half-width. All the simulations presented in this report, as well as the sensitivity analyses, are performed using the FEFLOW model of the WASY Institute for Water Resources Planning and Systems Research Ltd.

The conceptual transport model simulates many processes in addition to the advection-dispersion process. The release mechanism and glass dissolution, sorption effects, matrix diffusion and radioactive decay are among the processes modeled. The parametric uncertainty analysis also extends to three of the transport parameters governing the glass dissolution process, the matrix diffusion process and local scale dispersion. The solution of the transport problem is performed using a numerical particle-tracking algorithm and a semi-analytical solution is used for the matrix diffusion studies.

Hydraulic conductivity data collected from six boreholes are analyzed to yield a best estimate for the homogeneous conductivity value and the range of uncertainty associated with this estimate. Temperature logs measured in several of the boreholes on the island are used to estimate groundwater recharge. Measurements of total porosity were made on numerous core samples obtained from four boreholes. There are no measurements for fracture porosity, and therefore, values for this parameter are selected based on reported values from the literature.

Batch sorption experiments were performed using cores collected from the Cannikin emplacement well. Sorption on both basalt and breccia was investigated for strontium, cesium, and lead dissolved in water of basically seawater composition. The high ionic strength of the solution and rock properties resulted in no significant sorption for any ion except lead. The resulting distribution coefficient for lead was used to obtain a surface-based sorption constant for retardation of strongly sorbing radionuclides in fractures. Effective diffusion coefficients were also determined

for the cores and used to determine the matrix diffusion parameter controlling mass transfer from high-velocity fracture flowpaths into the surrounding matrix. This parameter is also dependent on the fracture half-aperture, estimated as 5×10^{-4} m from literature values.

A detailed preliminary uncertainty analysis is performed for Milrow to evaluate the impact of uncertainties of individual parameters on transport results. The numerical model is individually calibrated for each test site using site-specific chloride concentration and head data. After calibration, the Milrow configuration is used to perform a parametric uncertainty analysis, where we vary one parameter at a time and evaluate the effects of this change on the results of the transport solutions. This analysis resulted in reducing the list of uncertain parameters to only three significant parameters (recharge, conductivity and porosity) and fixing the rest of the parameters at their best estimate.

The final modeling stage performed for all three shots utilized multiple realizations of the flow field generated by considering random combinations of recharge, conductivity and porosity drawn at random from their respective distributions. All transport parameters were fixed at their best estimate. The ensemble of transport solutions is then analyzed in terms of the mass arrival to the seafloor, the first arrival time and the location and time where peak fluxes and concentrations occur. An additional sensitivity case is also presented for addressing the effect of changing the strength of the matrix diffusion process.

Transport results indicated that the radionuclide movement at Long Shot is much faster than at Milrow and Cannikin. That is due to the location of the cavity being very shallow as compared to the other two tests. The arrival time of the peaks of mass flux and concentration for tritium is in the order of 20 to 30 years for Long Shot and 100 to 125 years for Milrow and Cannikin. This led to higher mass fluxes and concentrations breaking through at Long Shot than at Cannikin or Milrow with the difference depending on the radionuclide's half-life.

In addition to the three uncertain parameters considered (recharge, conductivity and fracture porosity), the results are also very sensitive to the parameters affecting the diffusion of radionuclides into the rock matrix. This sensitivity is greater for radionuclides with short half-lives. Uncertainties primarily in determining the fracture aperture lead to great uncertainty in the matrix diffusion strength. In addition, the semi-analytical solution employed for addressing the matrix diffusion process is based on many simplifying assumptions that are not necessarily satisfied in the field.

A variety of sensitivity studies are presented. With the exception of evaluating matrix diffusion, the alternate scenarios are performed on several realizations selected to be representative of the gamut of flow behavior. As a result, the sensitivity results are not directly comparable to the Monte Carlo results, but do allow identification of the general magnitude of impact that process uncertainty contributes. A variety of numerical solution issues, matrix diffusion, colloid transport, uncertainty in island half-width, sea level changes, and geothermal processes are evaluated using the two-dimensional models. The impact of the two-dimensional simplification, flow in the rubble chimney, Cannikin Lake nuclear heat and flow in fault zones are all evaluated with three-dimensional models.

The presence of the nuclear chimney, with its high vertical conductivity, is found to dominate many of the other conceptualizations (the chimneys are included in the base-case Monte-Carlo calculations). Numerical solution issues, sea level changes, geothermal processes, the two-dimensional simplification, Cannikin Lake, and fault zones all have relatively limited impact on transport results for the realizations analyzed, or result in significantly less transport than the base case. Matrix diffusion, colloid transport, island half-width, and nuclear heat are potentially more significant. The results of the risk assessment will determine whether the uncertainties identified here are of potential significance or can be tolerated within an acceptable margin of safety.

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PUBLICATIONS RESULTING FROM THIS WORK

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LIST OF ACRONYMS

AEC	Atomic Energy Commission
AMSL	above mean sea level
DRI	Desert Resarch Institute
DOE	Department of Energy
GUI	graphical user interface
GW	groundwater
IAEA	International Atomic Energy Association
MPC	maximum permissible concentration
MSL	mean sea level
NTS	Nevada Test Site
RSC	relative specific capacity
STS	Supplemental Test Site
USGS	U.S. Geological Survey

LIST OF SYMBOLS

A_{sp}	Specific surface area
A_L	Longitudinal macrodispersivity
A_T	Transverse macrodispersivity
b	Fracture half aperture
C	Radionuclide concentration
C_0	Initial concentration
c_s	Specific heat of rock
c_0	Specific heat of fluid
D^*	Effective diffusion coefficient
$D_m{}^*$	Effective diffusion coefficient in the matrix
$\mathbf{D}$	Local hydrodynamic dispersion tensor
e	Anisotropy ratio
IAP	Ion activity product
K	Hydraulic conductivity
K_{xx}	Horizontal hydraulic conductivity
K_{zz}	Vertical hydraulic conductivity
K_T	Equilibrium constant
K_d	Distribution coefficient
K_a	Surface-based sorption constant
K_f	Freundlich isotherm parameter
k	Thermal conductivity
k_g	Glass dissolution rate
k_l	Linear rate constant
κ	Matrix diffusion parameter
M_0	Initial mass of radionuclides
n	Freundlich isotherm exponent
NP	Number of particles in the random walk simulations
NP_G^t	Number of particles released via glass dissolution at time t
Q	Total solute mass flux
q	Point solute mass flux
R	Retardation factor in the fracture
R_c	Cavity radius
$Rech$	Recharge
R_m	Retardation factor in the matrix

S_s	Specific storage
t	Time
T	Temperature
V	Velocity vector
α_L	Longitudinal local dispersivity
α_T	Transverse local dispersivity
β_L	Thermal longitudinal dispersivity
β_T	Thermal transverse dispersivity
Δt	Time step
Δx	Spatial grid size
γ	Retention function
λ	Decay rate
λ_s	Rock thermal conductivity
λ_0	Water thermal conductivity
μ	Undecayed moment
μ_d	Decayed moment
μ_0	Water viscosity
ω	Radionuclide's half life
ρ_0	Fluid density
σ	Standard deviation
θ	Fracture porosity
θ_m	Matrix porosity
z	Mass transfer of a chemical species into aqueous solution per unit surface area of solid